Cardiovascular Imaging at 3T

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Introduction

The challenges for cardiac MR imaging range in a magic triangle of spatial and temporal resolution, signal-to-noise ratio and the limitations induced by the need for breath-hold imaging. With the advent of multi-channel whole-body MRI systems at 3Tesla, these limitations can now be overcome. Parallel acquisition techniques (PAT) allow increasing temporal or spatial resolution at virtually no costs in acquisition time. The higher field strength at 3T makes up for the loss of signal-to-noise ratio (SNR) induced by fast scanning with PAT. With the combination of PAT and 3T, real-time acquisitions have now become feasible obviating the need for breath-hold cardiac MRI.

Basic Concepts of Parallel Imaging at 3T

The concept of parallel imaging is the under-sampling of k-space by sampling only every n^{th} line in k-space compared to a full k-space acquisition. This reduces the acquisition time to 1/n of the non-accelerated acquisition and is typically referred to as imaging with an acceleration or reduction factor R. However parallel imaging requires multi-element coils for spatially resolved signal detection. The so-called coil sensitivity profiles are then used to reconstruct an image equivalent to a full k-space acquisition without increase in acquisition time and without aliasing artifacts caused by under-sampling. Parallel imaging and 3T have a unique synergistic effect: one limitation of 3T MRI is the higher specific absorption rate (SAR) induced by the higher Larmor frequency of the RF pulses, which is effectively compensated by parallel imaging where fewer RF pulses are required to sample an equivalent data set. On the other hand the lower SNR induced by the use of PAT which decreases the SNR by at least a factor of one over the square root of the acceleration factor is compensated by the higher SNR at 3T. Looking at the performance of PAT at 3T compared to 1.5T, the loss of SNR introduced by an acceleration factor of R=4 with parallel imaging is approximately compensated by the SNR increase of a factor of 2 from 1.5 to 3.0T. Therefore a four-fold gain in acquisition speed is feasible at 3 Tesla with virtually no penalty in SNR compared to 1.5T. This methodological advantages result in a number of new possibilities in cardiac MRI at 3T: • Multi-breath-hold imaging can eventually become single breath-hold imaging. • a 128-matrix can eventually be increased to a 256-matrix. • Gated breath-hold CINE MRI may be replaced by free breathing real-time CINE MRI. • 2D CINE cardiac MRI may be replaced by 3D CINE cardiac MRI.

Cardiac CINE MRI

Cardiac cine MRI at 3 Tesla was initially not considered the primary application for 3T due to problems with the high SAR and a number of artifacts particularly for the use of steady-state free precession techniques (SSFP). For SSFP sequences, the absolute signal depends on the phase offset between $\pm\alpha$ rf pulses according to the formula: $\Delta\varphi = \Delta\omega\, TE$.

Due to the higher resonance frequency at 3 Tesla this phase offset is increased within one field-of-view thereby potentially resulting in a band-like artifact within the image. Recent improvements such as the variable frequency scout have overcome this limitation by intentionally varying the frequency and thus introducing an additional phase offset to shift the artifact outside the region interest. In one study, excellent correlations between cardiac function parameters at 1.5 T and 3.0 T were obtained and image quality for SSFP and spoiled-gradient echo (SGE) sequences was rated equal, although compared to SGE, SSFP was still more frequently prone to artifacts (1).

It has been shown that single breath-hold multi-slice cardiac MRI is feasible already at 1.5T. In a study by Wintersperger et al. 11 short axis slices using steady-state free precession (SSFP) cardiac functional analysis, have been feasible within a single breath-hold of ~20 heart beats (2). As it had been shown in other studies that temporal resolution is more critical for the accuracy of cardiac function analysis than spatial resolution (3), a temporal resolution of <50ms could have been maintained in this study with an acquisition matrix of 128 (2). For those studies typically an acceleration factor of R=2 was used applying either a GRAPPA (generalized auto-calibrating partially parallel acquisition) or a SENSE reconstruction algorithm. A limitation of the integrated auto-calibration in the GRAPPA algorithm in CINE imaging is caused by the fact that within each image frame additional central lines in k-space (reference lines) have to be acquired for auto-calibration of the coil sensitivity profiles. This results in a somewhat net loss of the effective acceleration factor R which is typically reduced by approximately 20-40% depending on the number of reference lines. More recent reconstruction algorithms such as TSENSE or TGRAPPA overcome this limitation by eliminating the need for additional reference line measurements by exploiting the data of an interleaved k-space line sampling covering the full k-space in subsequent dynamic CINE frames (4, 5). These techniques allow for a marked acceleration of CINE SSFP imaging as already shown at 1.5T by Reeder et al. with no significant loss in image quality and accuracy for cardiac functional analysis at R=3 (6). The combination of the TSENSE algorithm with higher field strengths and multi-channel MRI at 3T exceeds this performance by far. Four-fold faster cardiac acquisitions at full 256 matrix size with no loss in diagnostic accuracy compared to the non-accelerated images have been successfully demonstrated in clinical applications (7). In a study of 10 patients with myocardial infarction an excellent visualization of regional wall motion abnormalities and evaluation of global ventricular function was possible due to the high spatial and temporal resolution of a full 256 matrix and 50 ms temporal resolution in a multi-slice approach. This can be considered a gain in diagnostic accuracy for single breath-hold cardiac MRI compared to 1.5T, since it has been shown earlier that with real-time CINE regional function analysis is not reliably feasible at 1.5T due to the limits in spatial resolution. Another advantage of combining parallel imaging with multi-channel MRI systems at 3 T is, that the under-sampling of k-space with parallel acquisition techniques results in the possible use of higher flip angles for SSFP imaging. Due to the square relationship between the excitation angle and the specific absorption rate (SAR), cardiac MRI at 3T was traditionally limited to lower flip angles within the range of ~40° to 50°. Using TSENSE, flip angles of 60° or even higher could be realized resulting in a better blood-to-myocardium contrast. The contrast of multi-slice acquisitions at 3T accelerated by TSENSE is therefore comparable to non-accelerated images at 1.5T.

Delayed contrast enhancement

Also for the use in delayed enhancement (DE) imaging assessing myocardial infarction and viability, MRI at 3 Tesla allows for new possibilities and options. Despite all the effectiveness and value of DE imaging for assessment of myocardial infarction, this technique remains quite time intensive in clinical routine due to the need for inversion time adjustments to allow optimized contrast between the infarcted and normal myocardium. Already at 1.5T it had been shown that new techniques termed phase sensitive IR (PSIR) reconstruction, obviates the need for exact optimization of the inversion time (8). It has been demonstrated that PSIR allows an accurate assessment of the area of infarcted myocardium at virtually any arbitrary chosen inversion time (9). The combination with SSFP based acquisition speeds up data sampling allowing single breath-hold multi-slice coverage of the entire left ventricle for the exact assessment of the extent of myocardial infarction (10). However at 1.5T these images inherit higher image noise and are occasionally influenced by artifacts due to the ambiguousness of the phase information at low signal-to-noise ratios. At 3T the higher SNR allows for multi-slice single breath-holds SSFP PSIR imaging of the entire left ventricle with high image quality (11). The combination with PAT techniques like GRAPPA again allows preventing possible SAR limitations using SSFP at 3T. If TSENSE SSFP acquisitions of cardiac function and PSIR SSFP acquisition of delayed contrast enhancements are combined with multi-channel 3T MRI, a complete assessment of function and viability with high temporal and spatial resolution is feasible with only a few breath-holds. Comparing the accuracy of single breath-hold multi-slice acquisitions to time intensive multi-breathhold single slice acquisitions, it has been shown that the agreement between the two is higher at 3T compared to 1.5T.

Myocardial Perfusion

While CINE MRI and viability imaging have already been daily clinical routine techniques on 1.5T with sufficient high SNR levels, myocardial perfusion imaging has been a promising tool for the evaluation of coronary artery disease for years but never really took off for widespread use. This has been mainly based on limited SNR performance, artifacts and variable coexisting sequence techniques. At 3Tesla, one can envision that due the higher SNR the quality of saturation recovery gradient echo sequences (SR-GRE), the best evaluated standard in myocardial perfusion imaging, will substantially improve therefore enabling a reliable time-signal analysis and accurate assessment of myocardial perfusion. The gain in SNR could partially be invested in even higher spatial/temporal resolution using higher acceleration factors with PAT (e.g. TENSE) or enabling coverage of the entire short axis during first pass perfusion.

Further Developments in cardiac MRI

The introduction of 4D function analysis tools allows changing the approach for cardiac functional assessment (12). Although the use of the Simpsons' rule with a contiguous coverage along the entire short axis from the apex to the AV-valve plane has major benefits in terms of accuracy based on its 3D modeling, the valve plane itself could much better be identified in 2- and 4-chamber views. The 4D analysis software allows combining the information of long and short axis cardiac MRI including a computerized LV model thereby reducing the number of required short axis views. This can be combined with single breath-hold cardiac MRI at 3T

accelerated with TSENSE, since one breath-hold is sufficient to require 5-6 slices with sufficiently high temporal and spatial resolution for this type of analysis. Therefore one can envision a single breath-hold, highly accurate assessment of the LV function. With the advent of multi-channel scanner systems, new dedicated coil arrays might be developed that enable acceleration factors of 6 for TSENSE cine SSFP cardiac function analysis without substantial loss in diagnostic image quality (6). In combination with real-time acquisitions instead of segmented CINE techniques, this would allow new three-dimensional insights in the true physiologic cardiac action without the effects of intrathoracic pressure variations induced by the breath-hold. As already shown in preliminary studies this has promising clinical applications for the assessment of diseases such as constrictive pericarditis and the differentiation from restrictive cardiomyopathy (13).

MRA at 3 Tesla

In the past few years high-field scanners operating at 3.0 T have evolved from research to clinical scanners and have become widely available. The main motivation for the transition of contrast-enhanced 3D MR angiography (3D-CE-MRA) to 3.0 T is the theoretically doubled signal-to-noise ratio (SNR) compared to 1.5 T (14, 15). The higher SNR can be spent for either higher spatial resolution at the same examination time or faster image acquisition with unchanged spatial resolution. The longer T1 times at 3.0 T are also beneficial for MRA as they lead to improved background suppression (16) since the relaxivity of the injected gadolinium chelates remains relatively unchanged. Fortunately, the main problems of high-field imaging, i.e. increased susceptibility and dielectric artifacts, are not relevant with T1-weighted spoiled gradient echo sequences as employed for abdominal MRA. Solely, the specific absorption rate (SAR) which is increased by a factor of 4 at 3.0 T poses a potential problem. Therefore, the flip angle has to be lowered to less than 20° in most cases in order not to exceed the SAR threshold (15). Alternatively parallel imaging techniques may help to reduce the SAR to a certain degree if an additional delay after the shortened scan can be applied for the SAR calculation. The additional value of 3D-CE-MRA at 3 Tesla compared to 1.5 T has recently been demonstrated in preliminary studies for the carotids, renal and peripheral arteries (17).

Time-of-flight MRA at 3 Tesla without use of contrast agents can be already considered the new state-of-the art approach for non-invasive imaging of the intracranial vessels due to the high resolution of less than 0.5x0.5x0.5 mm and the excellent background suppression. In particular, the detection of very small intracerebral aneurysms can be substantially improved at 3T.

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